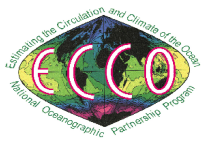


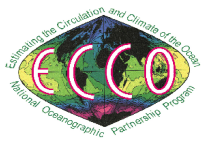
The coupled ocean/sea-ice adjoint model:

Current uses for sensitivity studies and state estimation

P. Heimbach[(1)], I. Fenty[(1)], D. Menemenlis[(2)],
M. Losch[(3)], J.M. Campin[(1)] ,C. Hill[(1)]

(1): MIT/EAPS, Cambridge, MA, USA
(2): JPL/NASA, Pasadena, CA, USA
(3): AWI, Bremerhaven, Germany

http://www.ecco-group.org
http://mitgcm.org

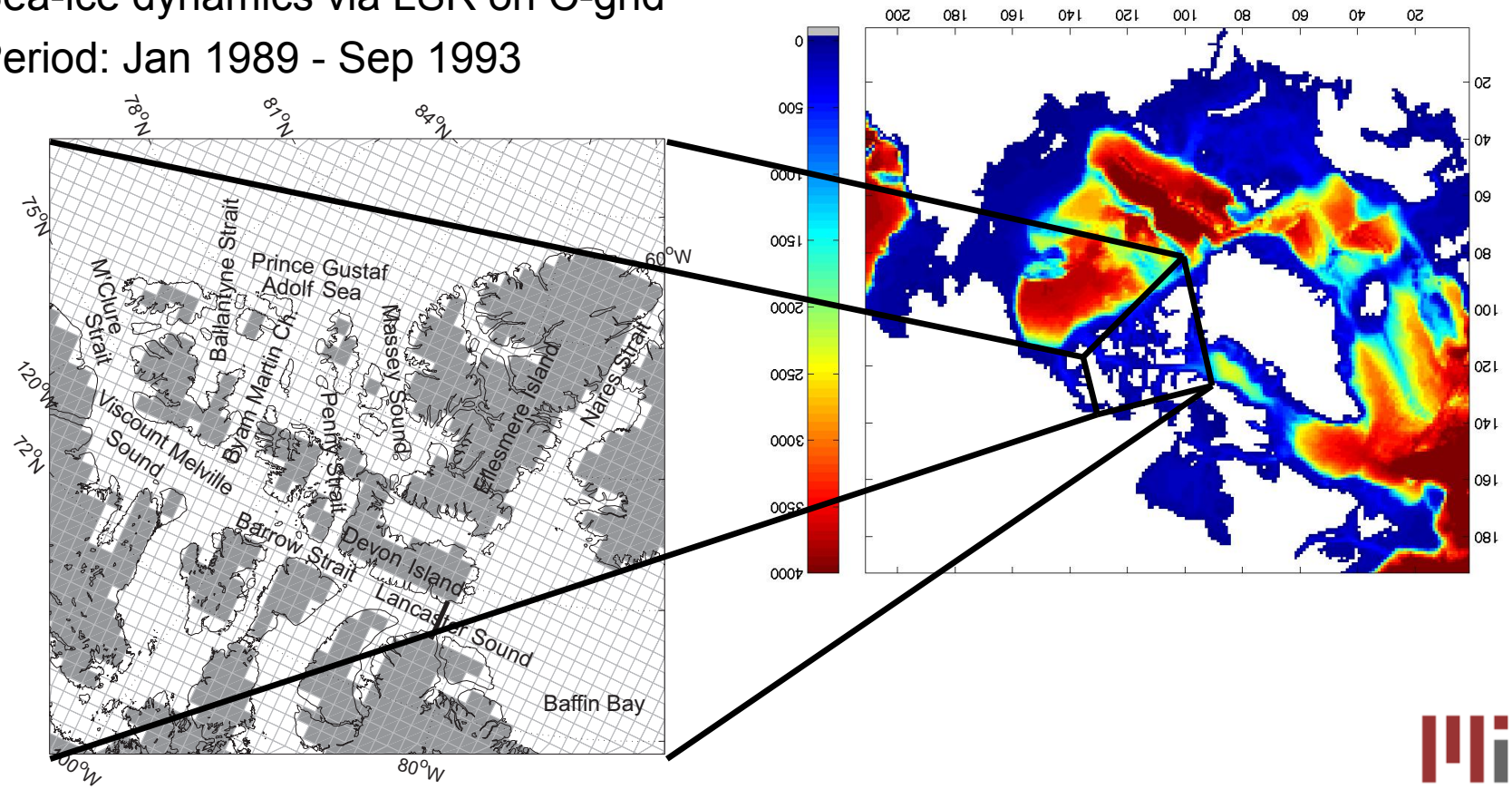


- Part 1

Sensitivity studies

Arctic configuration & Canadian Arctic Archipelago

- Coarsened Arctic face of the ECCO2 global cubed sphere (from ~18 km to ~36 km horizontal resolution)
- Ocean model uses, KPP & GM/Redi, but off in adjoint
- 6-hourly forcing via NCEP/NCAR atmospheric state, converted to open-ocean air-sea fluxes via Large & Yeager (2004)
- Sea-ice dynamics via LSR on C-grid
- Period: Jan 1989 - Sep 1993



The MITgcm sea-ice model

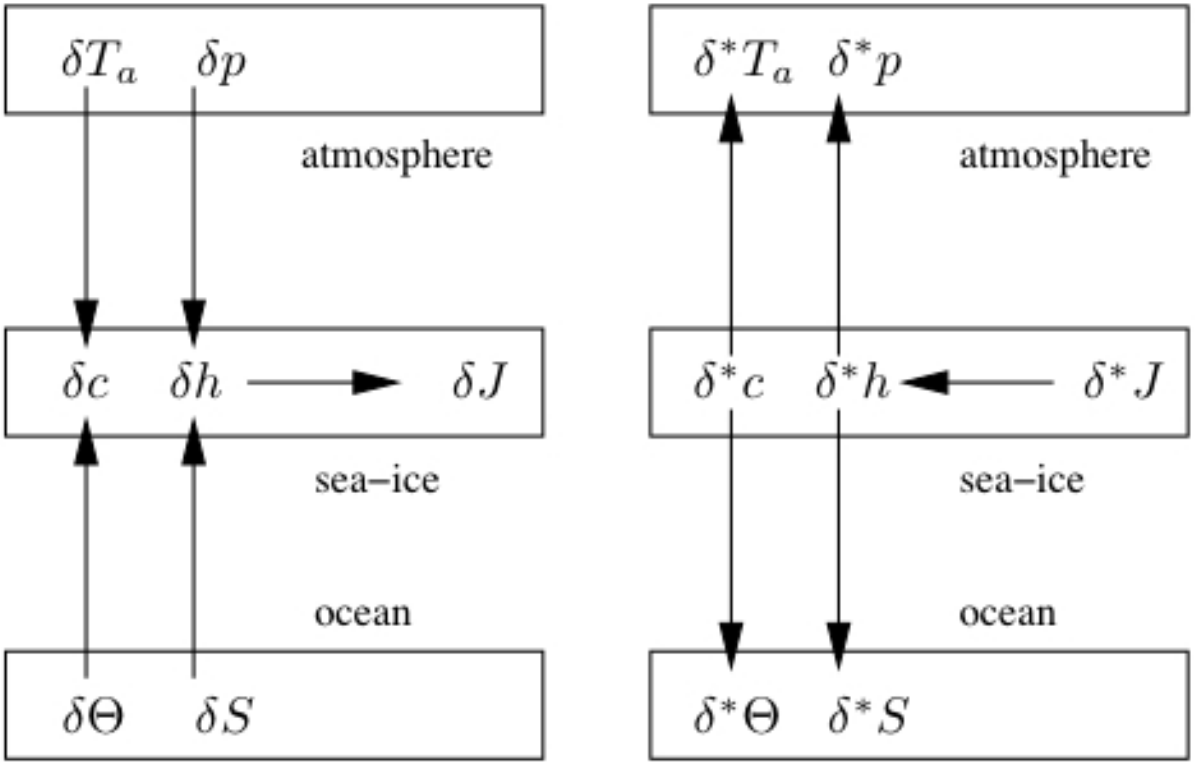
- Thermodynamics
  - Based on *Zhang & Hibler ,1997*
  - Two-category, zero-layer, snow melting and flooding *(Semtner, 1976; Washington & Parkinson, 1979)*
  - Sea ice loading and dynamic ocean topography *(Campin et al., 2008)*
  - Salt plume parameterization *(Nguyen et al., 2009)*

- Dynamics
  - Two solvers available for viscous-plastic (VP) rheology:
    - Line Successive Relaxation (LSR) implicit *(Zhang & Hibler, 1997)*
    - Elastic Viscous-Plastic (EVP) explicit *(Hunke & Dukowicz, 1997)*
  - Both ported on C-grid for use in generalized curvilinear grids
  - Various advection schemes available

- An exact (with respect to ***tangent linearity***) adjoint
  - generated via automatic differentiation tool TAF

- ***Losch et al. (submitted to Ocean Modelling, 2009a)***
- ***Heimbach et al. (submitted to Ocean Modelling, 2009b)***

The coupled ocean/sea-ice adjoint

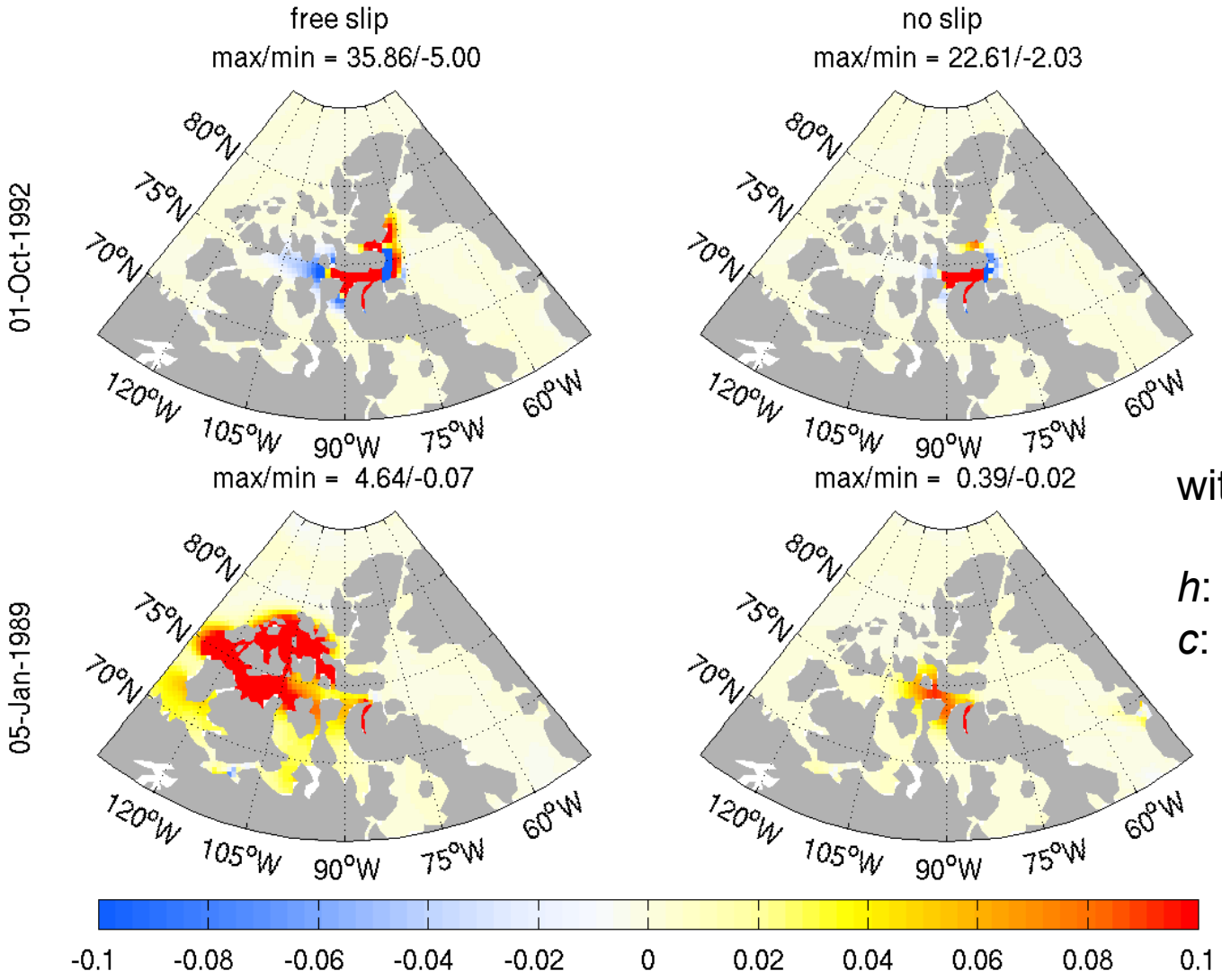


Sensitivity of ice export to all elements in the coupled state:

- **sea-ice** (e.g. thickness, concentration, snow cover)
- **ocean** (temperature, salinity, velocities)
- **atmospheric boundary condition** (SAT, specific humidity, precipitation, shortwave radiation, wind velocity)

$$J = \frac{1}{\rho_{fresh}} \int_{\text{Oct 92}}^{\text{Sep 93}} \int_{\text{LC}} (\rho\, h\, c + \rho_s h_s c)\, u\, ds\, dt$$

Adjoint sensitivity of solid (snow & ice) freshwater transport through Lancaster Sound



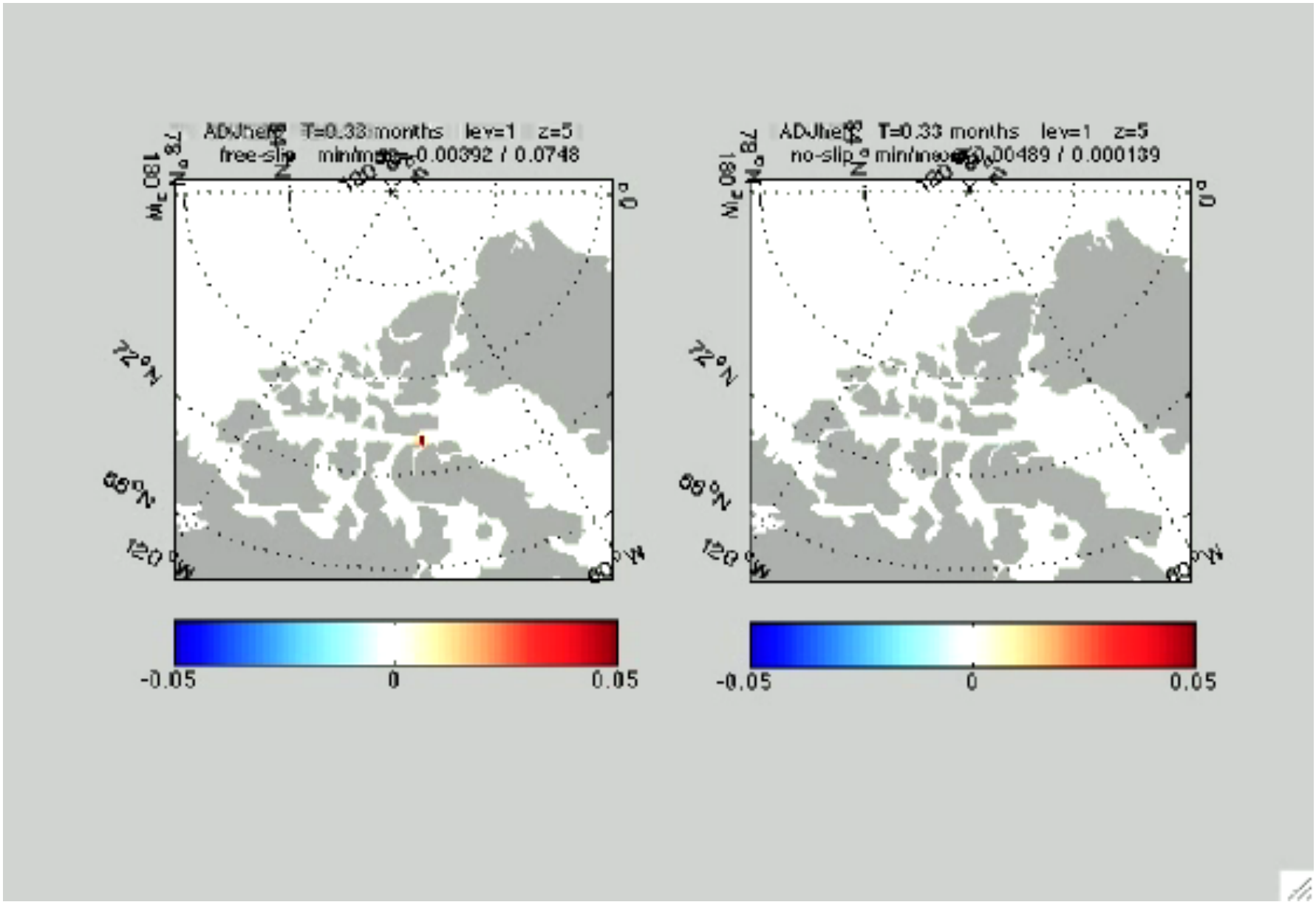
dJ / d(hc)

[m^2s^{-1}/m]

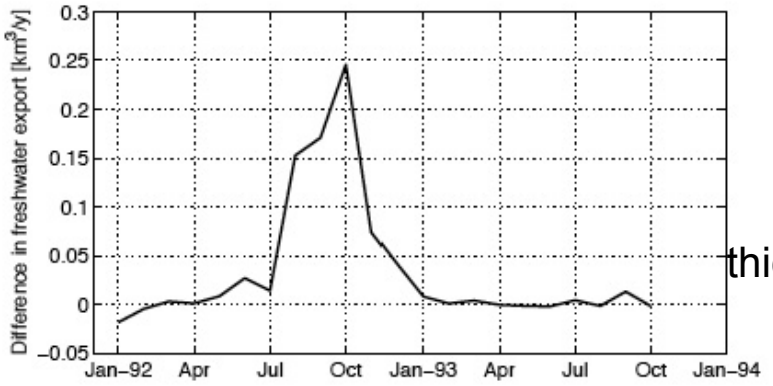
with

h: effective thickness
c: ice concentration

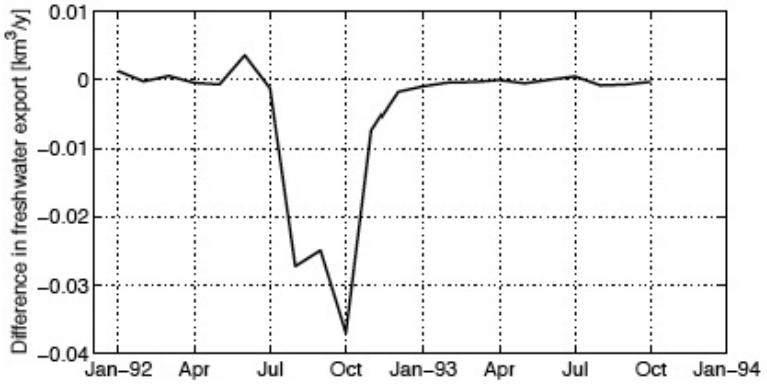
Adjoint sensitivity to ice thickness of solid freshwater transport through Lancaster Sound



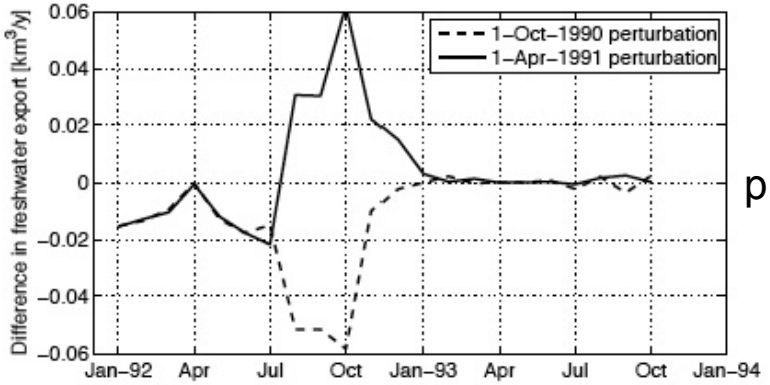
Perturbed - unperturbed ice export, testing the adjoint



ice thickness

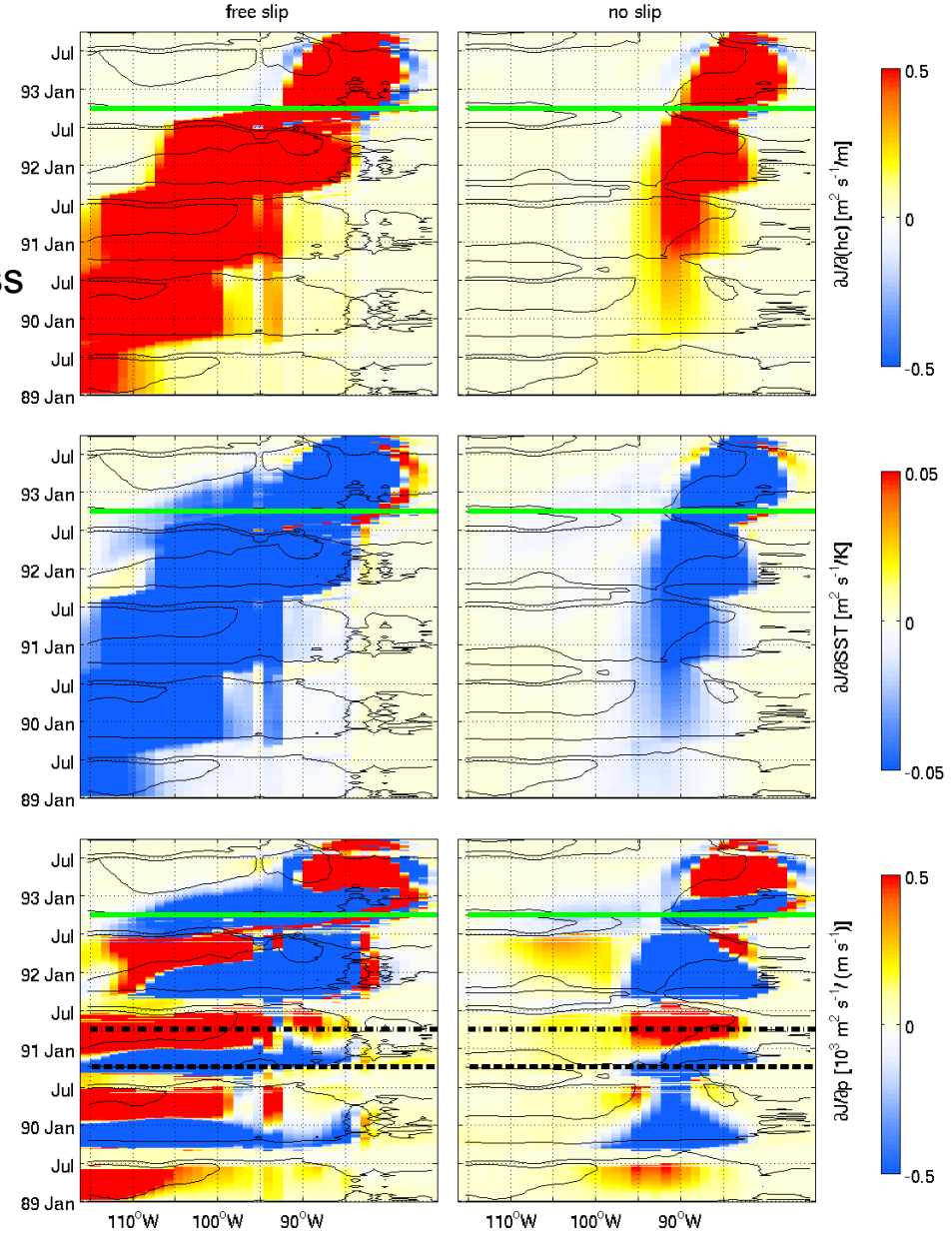


SST

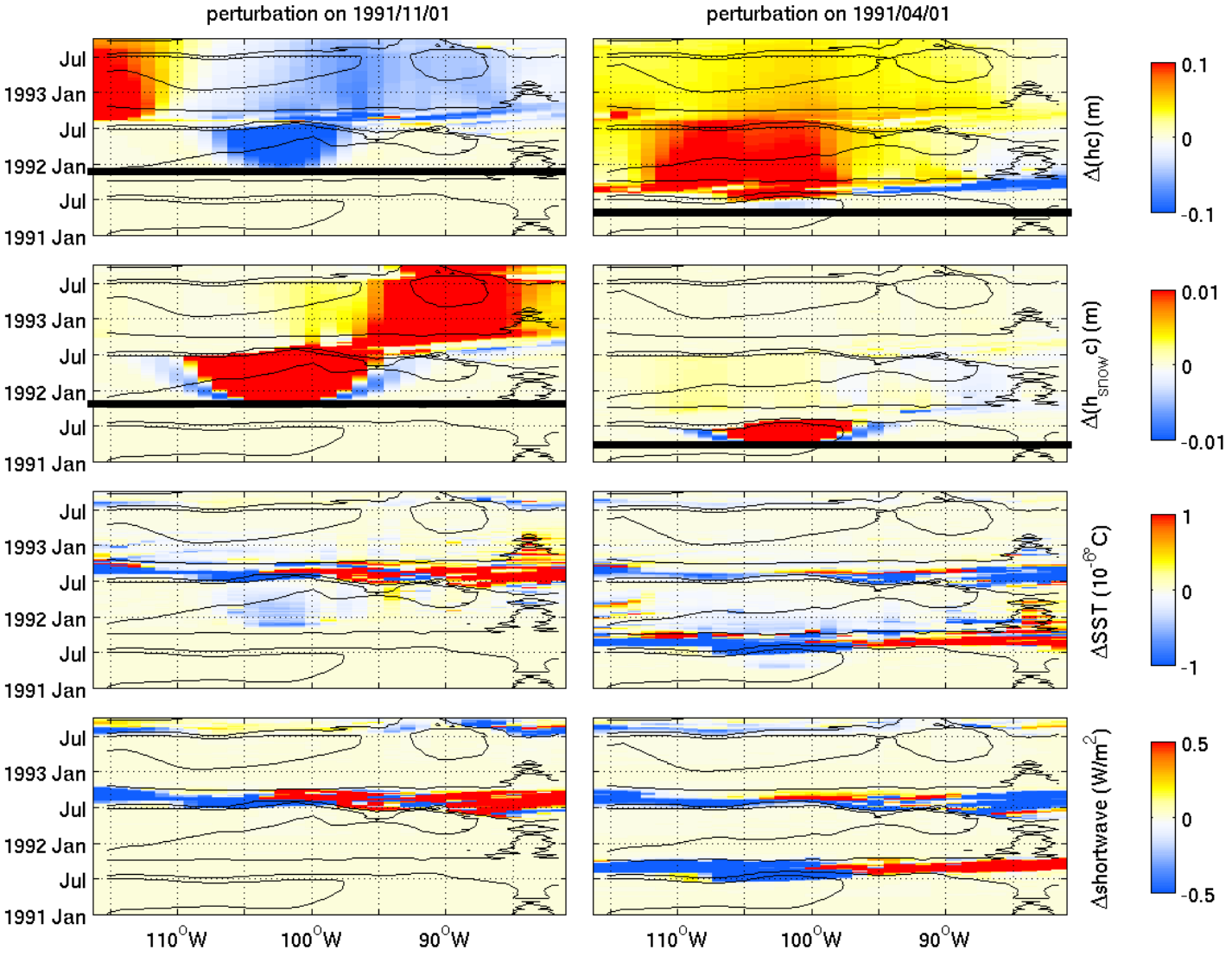


precip.

Longitude-time diagrams of sensitivities (slice through Lancaster Sound)

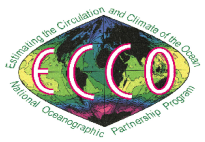


Origin of sign change in precipitation sensitivities



Some Results & Outlook

- Complement configuration sensitivities (e.g. free-slip vs. no-slip boundary conditions) through aspects related to state space
- Adjoint model generated via automatic differentiation
- Adjoint sensitivities reveal pathways of ice export influences as function of underlying ocean/atmosphere state
- May reveal unexpected sensitivity behavior (e.g. here, sign of precipitation sensitivities)
- A crucial step to ascertain useful gradients for state estimation, which is the ultimate goal
- Coupled problem ought to propagate sensitivities across the model components;
  ➔ could be explored in state estimation
  ➔ obs of one component constrain the other component

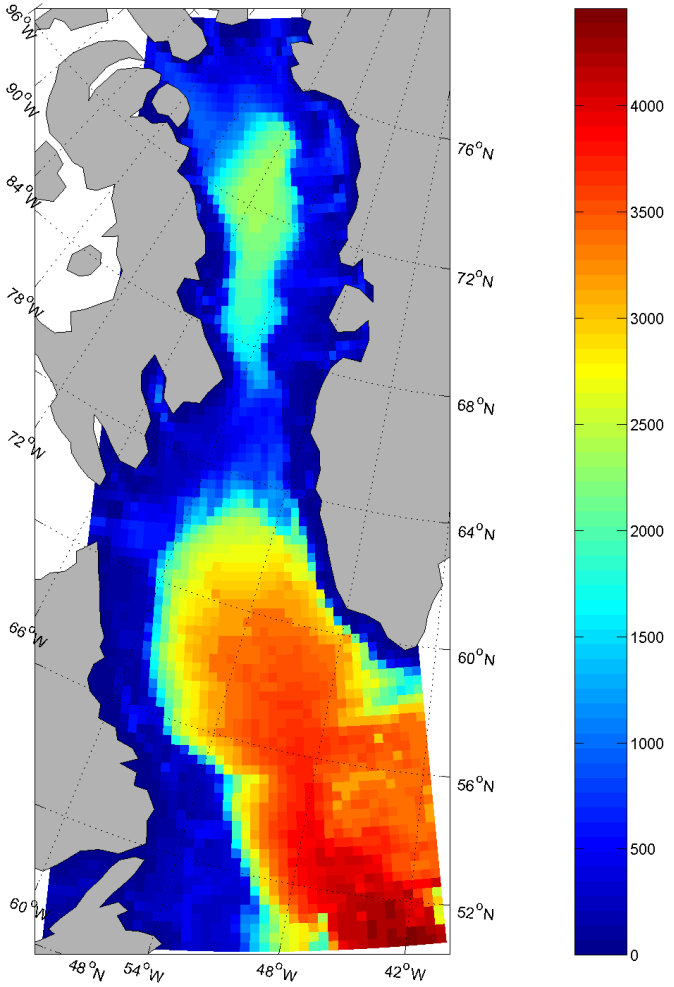


- Part 2

Coupled ocean/sea-ice state estimation

Sea-ice state estimation in a limited-area setup of the Labrador Sea

- MITgcm with Curvilinear Grid
  - 30 km x 30 km → 30 km x 16 km
  - 23 vertical levels
- 1.5 layer dynamic-thermodynamic sea ice model with snow
  - Stress-Strain rate based on Hibler (1980) ellipse
- Open boundaries
  - Weak sponge layers at Southern and Eastern edges
- Resolved Labrador and Greenland Shelves
  - Critical for sea ice production and advection
  - Important for boundary currents
- Computational efficient
  - Parallel: 1 real hr/ simulated year on 6 nodes

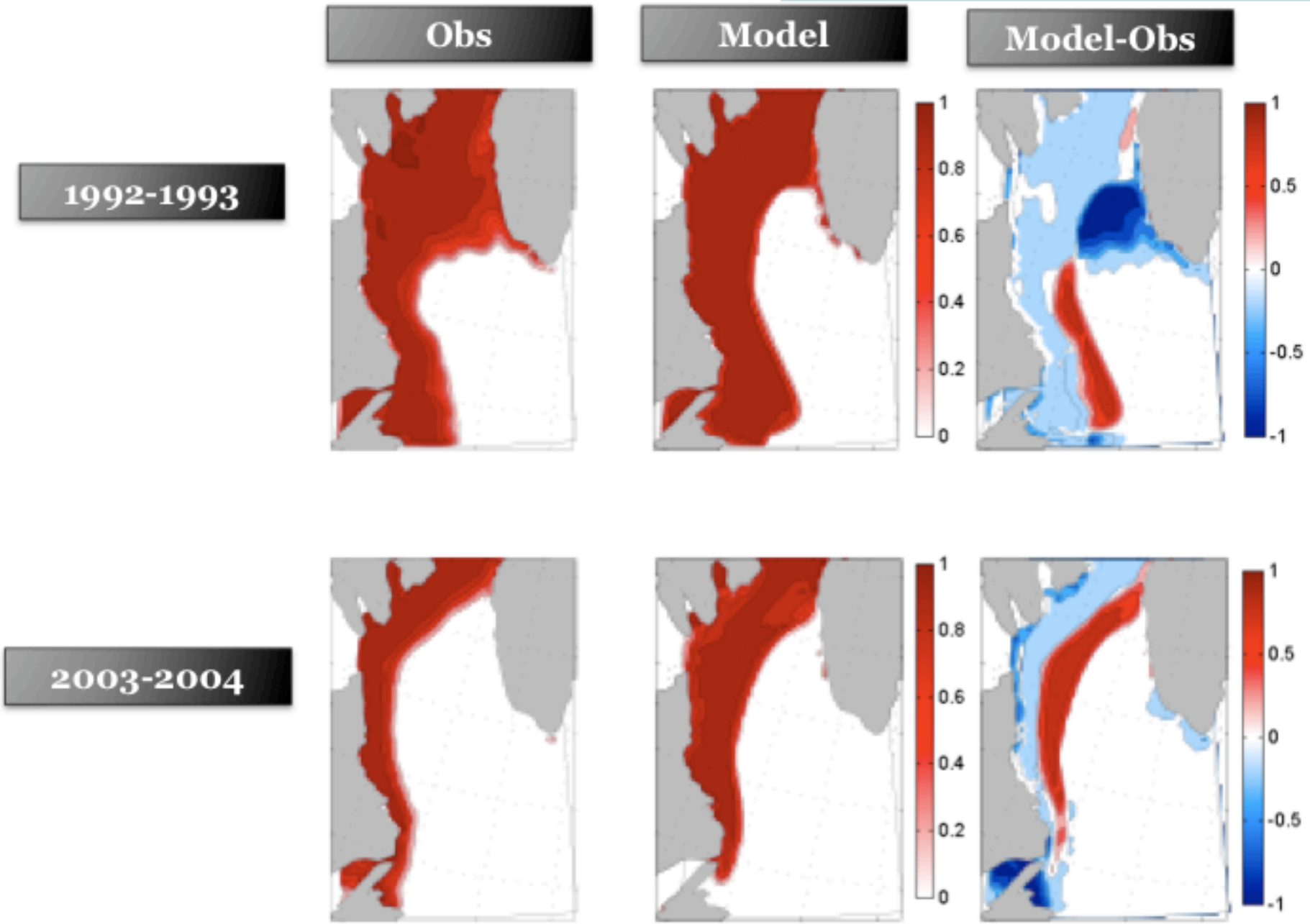


Bathymetry of model domain. Each distinct pixel is on cell

Ian Fenty (Ph.D. thesis, 2009)

Claims

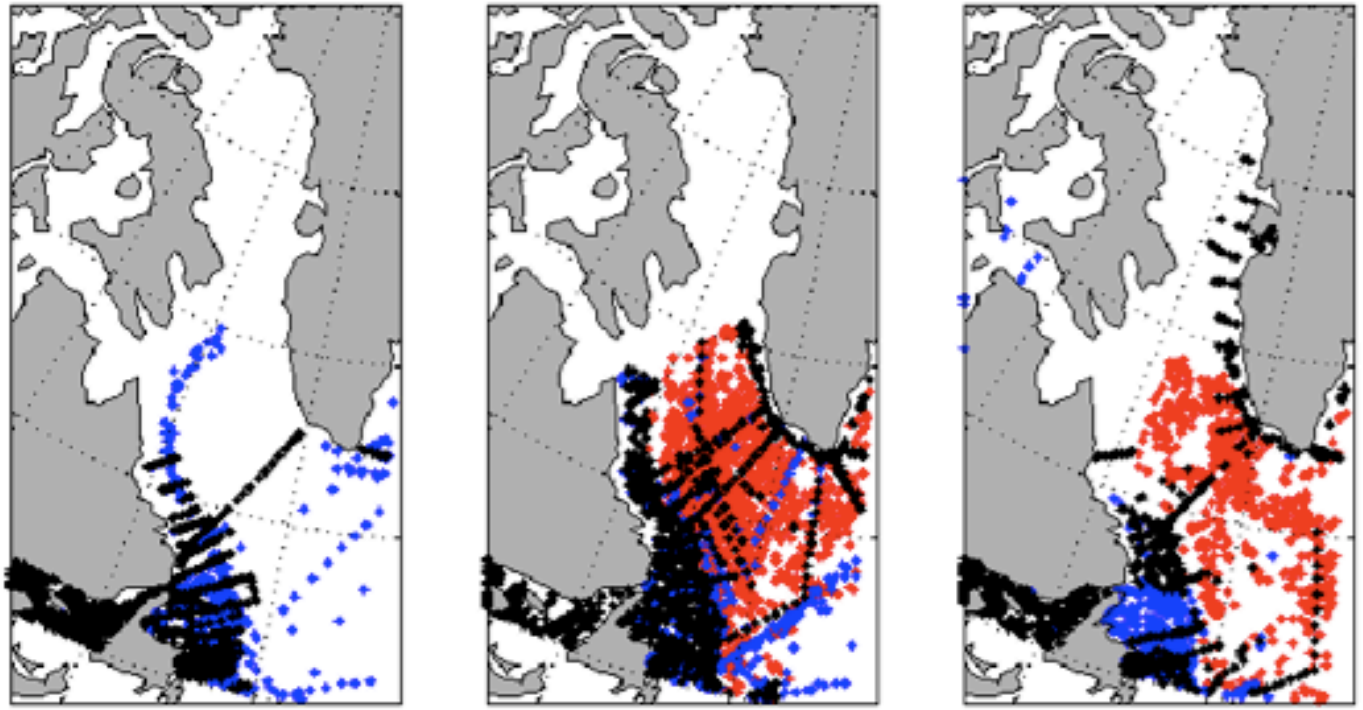
- Adjustments to initial and boundary conditions (within known uncertainties) can bring a coupled sea ice-ocean model into consistency with observations
  - "Probably all models are different and wrong"
- By modifying the sea ice cover these adjustments significantly affect air-sea fluxes
- Using the adjoint method to synthesize model and observations can reveal systematic errors and biases with both


Obs
Model
Model-Obs
1992-1993
2003-2004
1
0.8
0.6
0.4
0.2
0
1
0.5
0
-0.5
-1

Labrador Sea Ice State Estimation Setup

- Datasets:
  - XBT, ARGO, CTD, The Levitus-Goureski Climatology
  - NCEP reanalysis
  - ECCO initial and boundary conditions (IT199)
  - Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I (BOOTSTRAP algorithm)
  - Reynolds Daily 0.25 degree SST
- Uncertainties
  - In situ using representation method of Forget and Wunsch (2007)
  - NCEP gleaned from various sources where estimates have been made
  - Sea ice gleaned from various sources, higher for lower concentrations
- State Estimation Controls
  - Initial T,S
  - Time varying open boundary U,V,T,S
  - Atmospheric: T, q, U, radiation

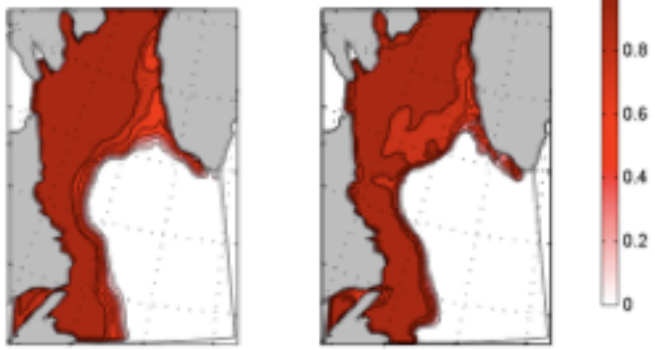
In situ Observations

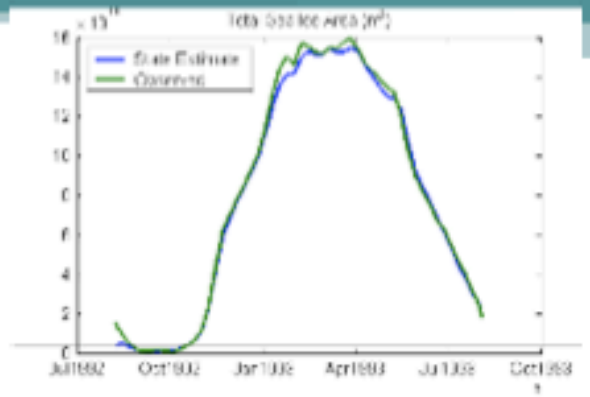


(a) 1992-1993 (b) 1996-1997 (c) 2003-2004

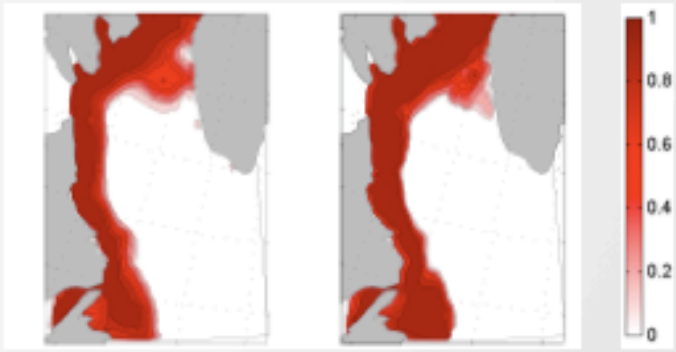
Figure 1-1: Location of profiles for each of the one year periods colors represent: black - CTD casts, red - profiling floats, blue - XBTs

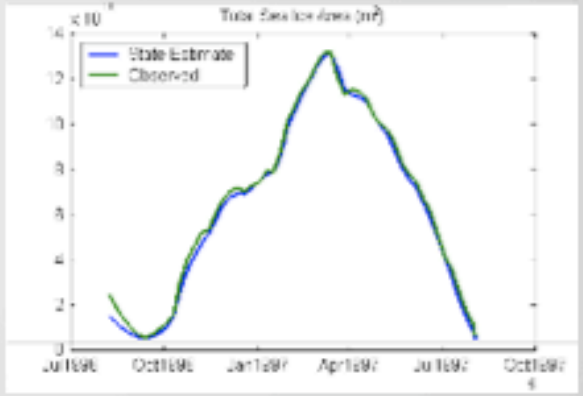
1992-1993



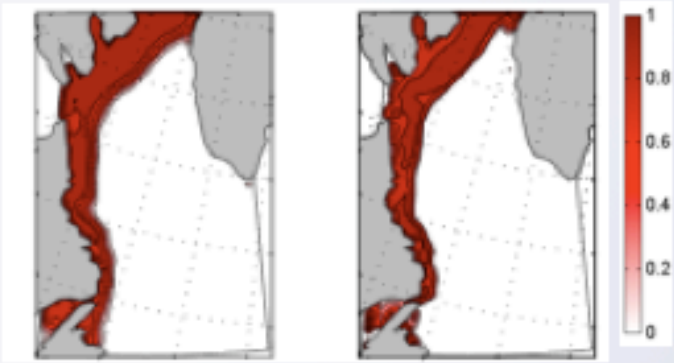


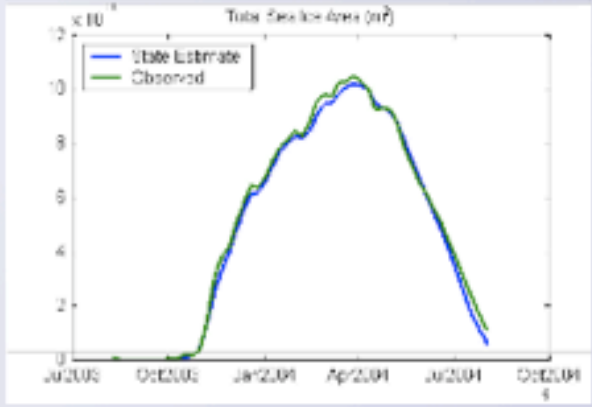
1996-1997



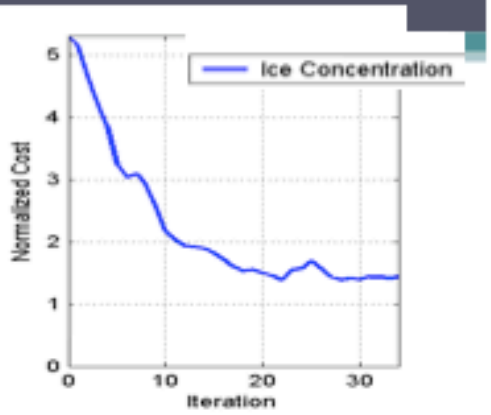


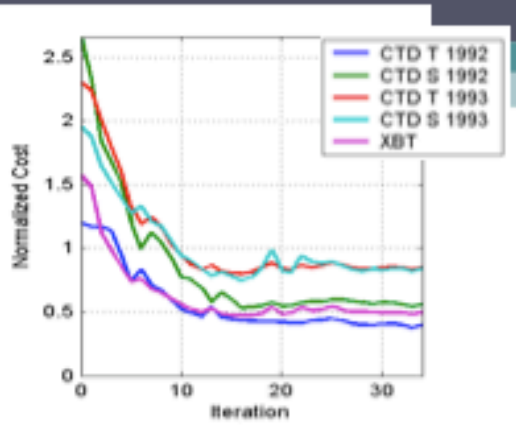
2003-2004

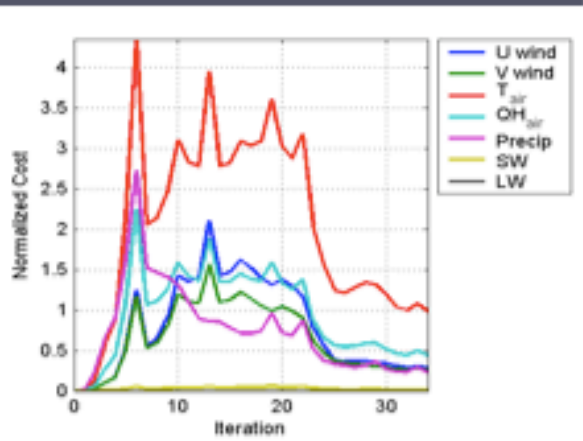




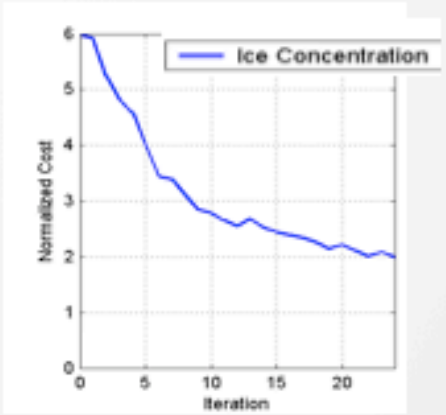
1992-1993

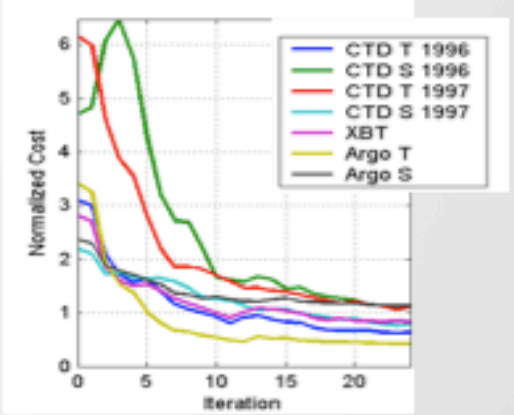


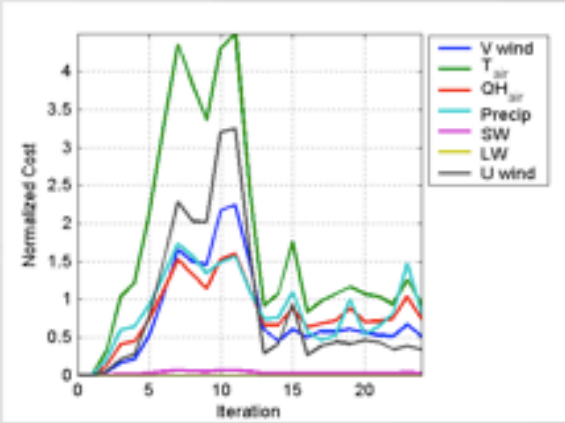




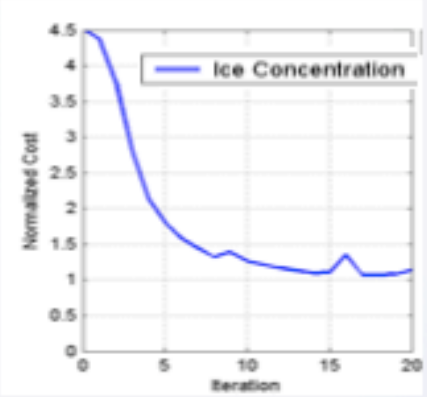
1996-1997

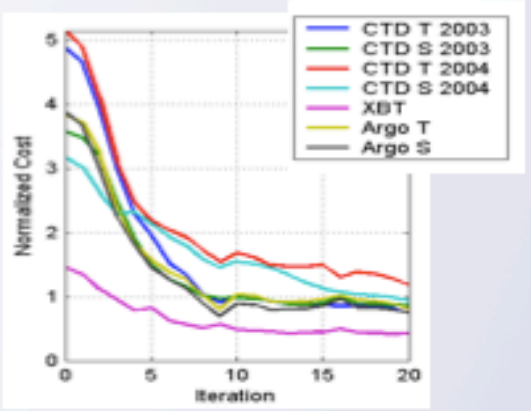


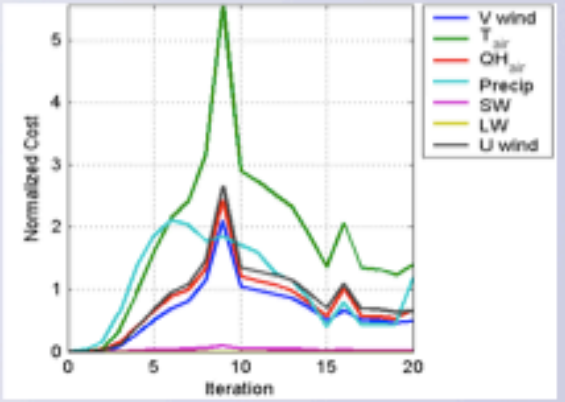


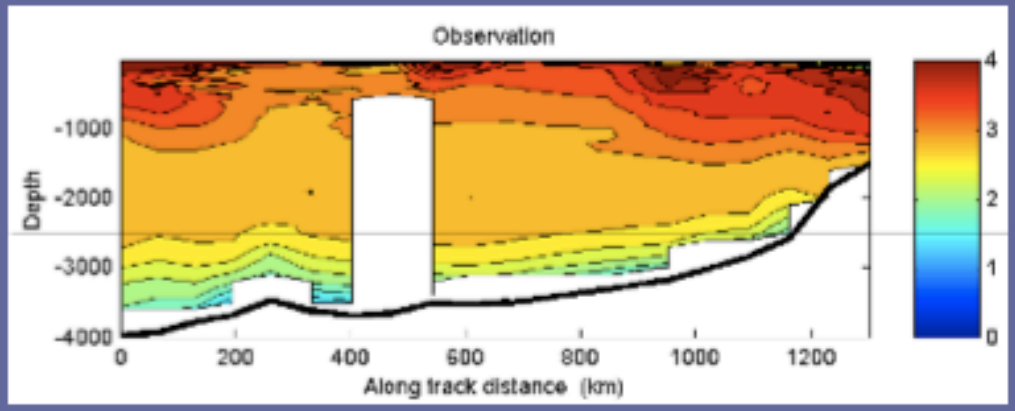


2003-2004

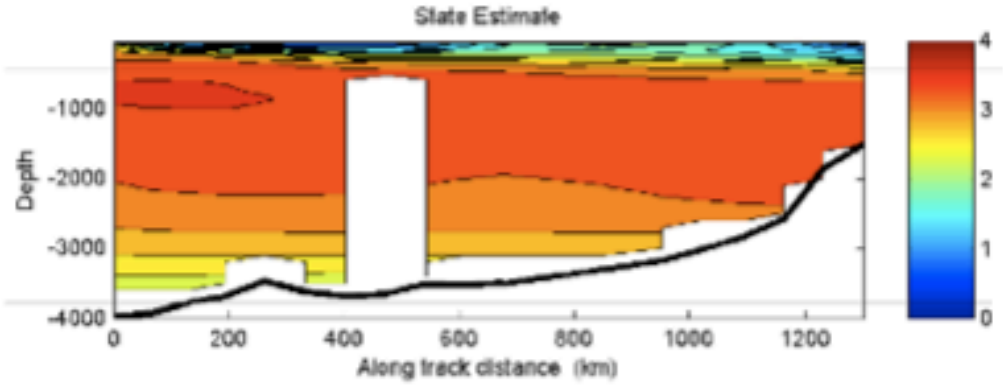




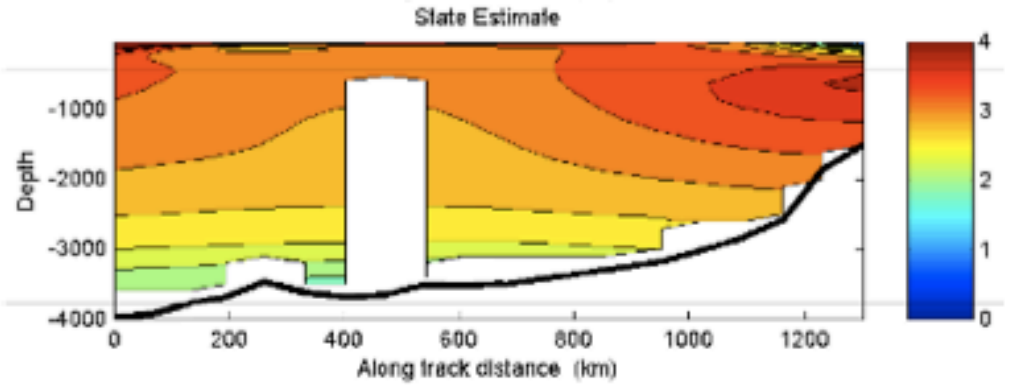


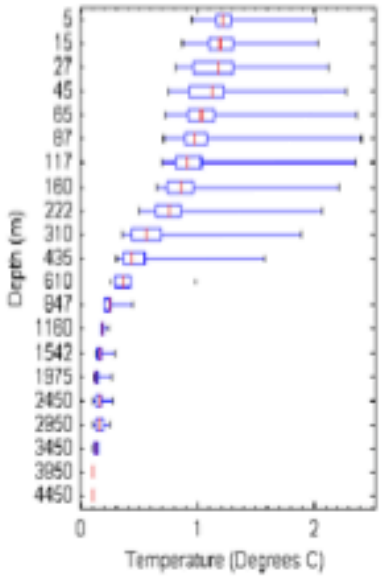


Iteration 0

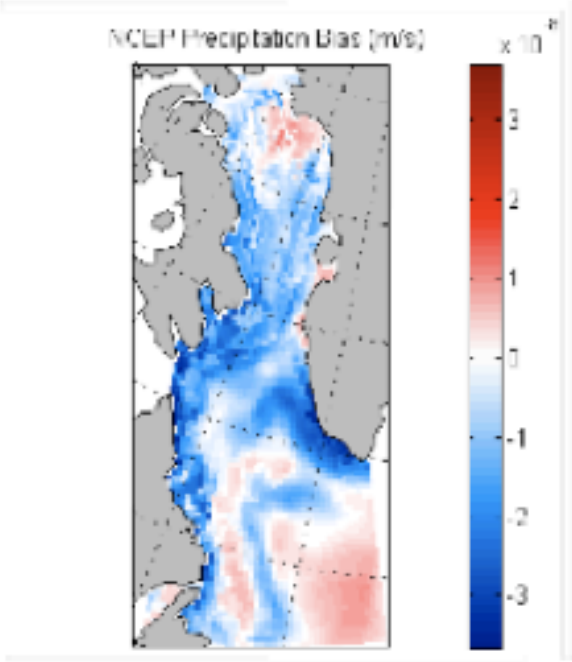


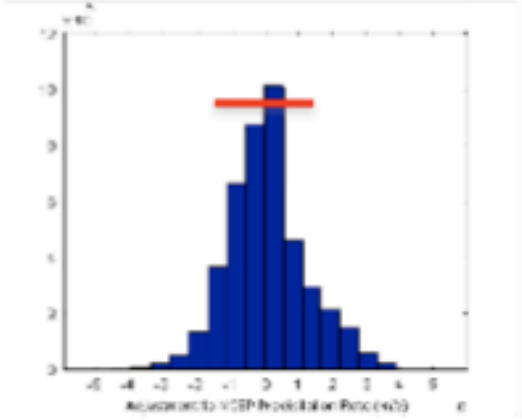
Iteration 33

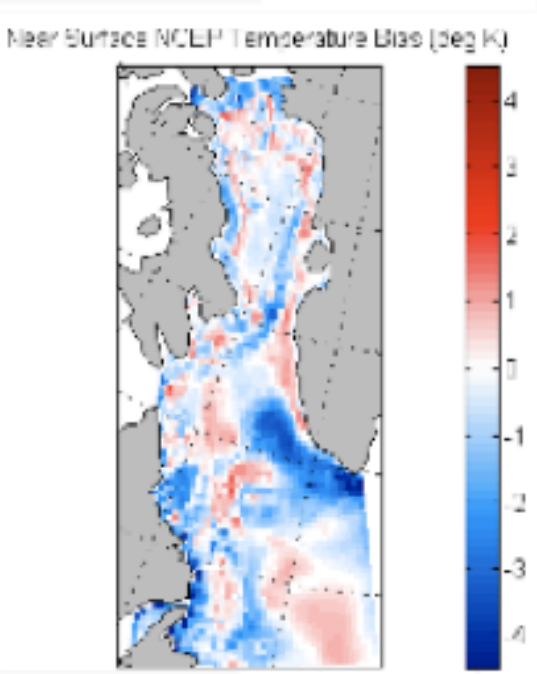


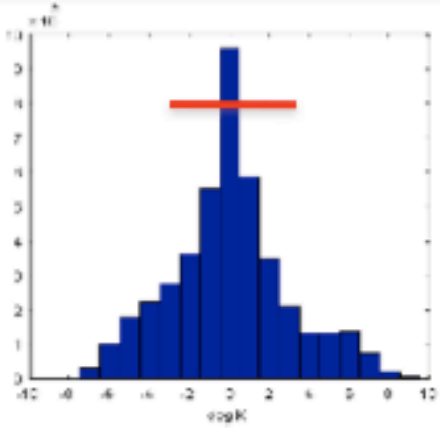


Atmospheric Adjustments









Conclusions

- The same model is shown to evolve quite differently based on reasonable adjustments to initial conditions and boundary forcing.
- Given the known model sensitivity to small changes to atmospheric forcing is there any information in the mean bias atmospheric adjustments that have utility beyond this specific model?
  - AOMIP participants could check this when basin-wide adjustments have been could be disseminated.

Thoughts about sea ice data assimilation

- Data sets
  - Prescribed or assimilated
- Atmospheric
  - Trustworthiness of renanalyses in high latitudes.
  - Validation in lower latitudes
  - Uncertainties not provided
- Choice of ocean state
  - Almost certainly the biggest unknown
  - Under many conditions direct assimilation of sea ice state is incompatible with ocean heat content/stratification
- Sea Ice
  - Different algorithms perform better under different ice conditions
  - Uncertainties are certainly time and space dependent
  - Not provided
- Formulation of sea ice model
  - Not obvious that more sophisticated sea ice models' adjoints will be useful
- Care of interpretation of adjustments
  - Model error is often overlooked
  - Atmospheric controls